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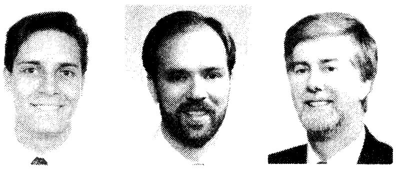
# Tests to Determine Performance of Deformed Welded Wire Fabric Stirrups



by Andrew Griezic, William D. Cook, and Denis Mitchell

*Two full-scale beams with cold-rolled, Grade 500 (Grade 75, ksi), deformed welded wire fabric U-stirrups were tested to assess the service and ultimate load performance of the welded wire fabric as shear reinforcement. By comparing the responses of these beams with two companion beams, reinforced with hot-rolled, Grade 400 (Grade 60, ksi) stirrups, it was demonstrated that the use of welded wire fabric resulted in better diagonal crack control and enabled large strains to be developed in the stirrups. These tests demonstrated that the full yield stress of Grade 500 reinforcement can be developed in the stirrups.*

*The predicted shear capacities of these beams, computed using the 1989 ACI Building Code expression, underestimated the actual strengths. The modified compression field theory provided a more accurate prediction of their capacities.*

**Keywords:** cracking (fracturing); ductility; reinforced concrete; **shear strength; stirrups; welded wire fabric.**

In North America, welded wire fabric (WWF) has been used in both precast concrete construction and slabs on grade. In Europe, welded wire fabric is used more extensively for precast and cast-in-place construction, including slabs, walls, beams, and columns. For example, by 1989, welded wire fabric constituted 29 and 50 percent of the total production of reinforcement in France and Holland, respectively. Between 1984 and 1989, the production of welded wire fabric doubled in France.[1] Studies[2] have shown that on-site time savings of 70 to 75 percent were realized by replacing conventional stirrups with prefabricated welded wire fabric stirrup cages. In Germany, welded wire fabric has been used for over 50 years, where it constitutes 40 percent of the reinforcement market. The popularity of welded wire fabric in Europe is attributed to the savings in placing the reinforcement on site and the approximately 15 percent reduction in steel area for this higher yield reinforcement. An additional benefit of welded wire fabric stirrup cages is the better dimensional control due to the fabrication process.

## PREVIOUS RESEARCH

Early research on the use of welded wire fabric focused on the effectiveness of smooth welded wire fabric as shear reinforcement due to its higher strength and different crack control characteristics. Leonhardt and Walther[3] and Taylor and El-Hammasi[4] both determined that smooth welded wire fabric is suitable for shear reinforcement and that it is effective for crack control, as long as it is properly anchored. Leonhardt and Walther also concluded that smaller wires with narrow spacings offer better crack control than larger bars with wider spacings.

More recently, researchers have been trying to determine whether deformed wire fabric further improves the crack control of reinforced concrete T-beams. Mansur, Lee, and Lee[5] considered the anchorage of deformed welded wire fabric and its behavior as shear reinforcement. They compared the response of T-beams reinforced with both smooth and deformed welded wire fabric to companion beams reinforced with conventional hot-rolled U-stirrups. The smooth wire cages improved the cracking behavior, resulting in smaller crack widths than the mild steel stirrups. They also found that the deformed wire further reduced the measured maximum crack widths. The smaller cracks in the specimens reinforced with welded wire fabric were partly due to the fact that these specimens had smaller stirrup spacings and had more stirrup steel than the companion beams. Mansur, Lee, and Lee[5,6] performed pullout tests and beam tests on different types of anchorage details for welded wire fabric. They concluded that deformed welded wire fabric had better anchorage and provided better crack control than smooth welded wire fabric.

While Pincheira, Rizkalla, and Attiogbe[7] concentrated on monitoring the behavior of deformed welded wire fabric under cyclic loading, they also performed some static tests on T-beams reinforced with deformed welded wire fabric. The shear reinforcement used in their tests consisted of a single sheet of welded wire fabric designed to replace an arrangement of conventional single-leg stirrups. They concluded that the deformed welded wire fabric offered a slight improve-

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ment of the crack control over conventional U-shaped or single-leg stirrups. Their results substantiate the findings of Mansur, Lee, and Lee.[6]

## RESEARCH SIGNIFICANCE

In spite of the research that has been carried out, there are three questions that remain unanswered. One question is whether or not conventional Grade 400 stirrups can be replaced with Grade 500 deformed welded wire fabric with an equal yield force ($A_v f_y / s$). In addition, it should be determined whether or not welded wire fabric can adequately control cracking and whether it can exhibit sufficient ductility to redistribute the stresses in the stirrups.

## CODE REQUIREMENTS FOR WELDED WIRE FABRIC AS SHEAR REINFORCEMENT

The maximum yield strength to be used in shear design calculations is limited to 400 MPa (60 ksi) according to ACI 318M-89[8] to provide adequate control of diagonal crack widths. Hence, using Grade 500 welded wire fabric, instead of Grade 400 reinforcing bars as stirrups, would not lead to a reduction of the amount ($A_v/s$) of stirrups required.

ACI 318M-89 gives alternative means of anchoring welded plain wire fabric U-stirrups, and the joint PCI/WRI Committee[9] gives guidance on details for anchoring plain or deformed single-leg WWF. No guidance is given on the beneficial effects of providing deformations on the anchorage details of WWF U-stirrups.

The Canadian Standards Association (CSA A23.3-M84)[10] has an additional requirement that welded wire fabric to be used as shear reinforcement must undergo a minimum elongation of 4 percent over a gage length of 100 mm. The gage length must include at least one cross wire. This requirement was included to insure that the WWF stirrups are capable of developing significant strains prior to failure.

## DESCRIPTION OF TEST SPECIMENS

Two full-scale test specimens, typical of cast-in-place T-beams in one-way floor slab construction, were tested under simulated uniform loading. Beams A500 and B500 had clear spans of 3.8 and 4.8 m, and were subjected to high and moderate shear levels, respectively. Fig. 1 shows the elevation views and cross sections of both beams. The shear reinforcement consisted of a stirrup cage constructed from deformed WWF. The welded wire fabric was made with 8-mm-diameter, Grade 500, cold-rolled deformed wire bent to form the stirrup cages. Anchorage of the stirrups near the top of the beam was provided by two 8-mm-diameter deformed wires welded to each stirrup leg, in accordance with ACI 318M-89.[8] An additional 8-mm-diameter deformed wire was welded to the bottom of the stirrup cage to maintain the shape of the assembly during transportation and placement.

The purpose of these tests was to compare the responses of Beams A500 and B500 with the responses of two companion beams, A400 and B400, reinforced with Grade 400,

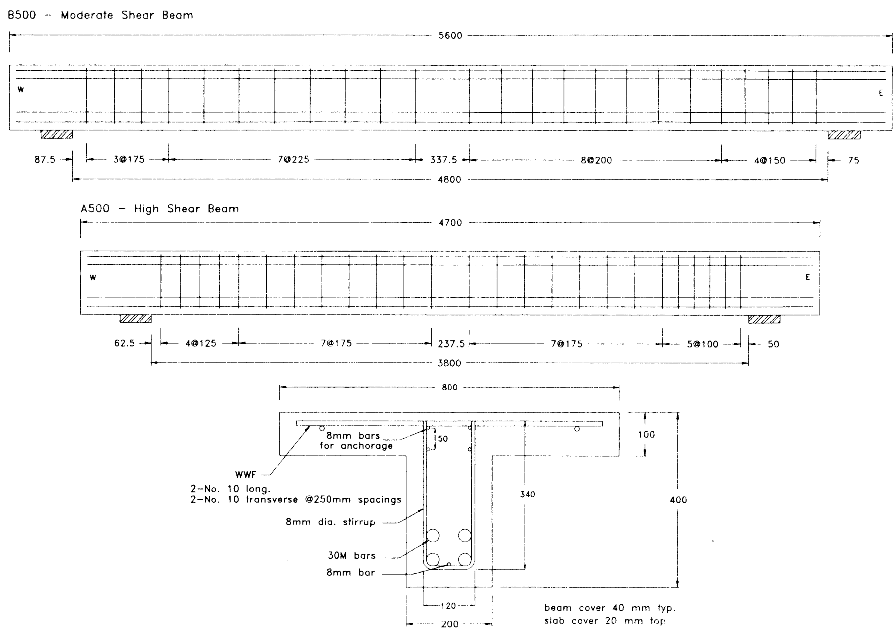


*Fig. 1—Reinforcement details of Beams A500 and B500*

hot-rolled No. 3 (9.5-mm-diameter) U-shaped stirrups, tested by Mailhot.[11] The spacings of the stirrups in the different regions of Beams A500 and B500 were chosen such that they had the same yield force per unit length (i.e., the same $A_v f_y / s$) as provided in the companion beams. Fig. 2 shows the reinforcement details of the companion specimens tested by Mailhot. The measured values of yield stress rather than the nominal values for both types of steel were used in determining the required stirrup spacing. To use the standard fabrication process, the spacing of the WWF stirrups were chosen as multiples of 25 mm. This resulted in a maximum variation of approximately 7 percent from the desired stirrup spacing. For ease of fabrication, a stirrup cage was fabricated for each end of the beams. All four beams had a concrete cover of 40 mm, measured to the stirrups.

Table 1 summarizes the design loads and reinforcement amounts used for the four beams. Beams A500 and A400 were designed for a factored loading $w_f$ of about 160 kN/m, while Specimens B500 and B400 were designed for a factored loading $w_f$ of 100 kN/m using the design equations of CSA A23.3-M84.[10] The code expressions of ACI 318M-89 would predict that all four beams would fail in shear and, furthermore, all four beams have regions in which stirrup spacings violate the spacing limit of $d/2$. The longitudinal reinforcement for all of the beams consisted of four No. 30 bars with a specified yield stress of 400 MPa. A smaller amount of shear reinforcement was provided in the west end of each beam than in the east end. Therefore, the shear strength was controlled by the west end, and the east end provided an opportunity to investigate the influence of amount and spacing of shear reinforcement on the diagonal crack control characteristics.

## MATERIAL PROPERTIES

According to ASTM A496-86[12] and ASTM A497-86,[12] the cold-rolled deformed wire that constitutes welded wire fabric must have a minimum specified yield strength of 485 MPa (70 ksi) and a minimum tensile strength of 550 MPa (85 ksi). The properties of the reinforcement are given in Table 2.

**Table 1 — Design parameters and reinforcement details of T-beams**

| Beam $f'_c$, MPa | Design service load $w_{se}$, kN/m | Design factored load $w_f$, kN/m | Clear span $\ell_n$, m | Type of Stirrups | West end stirrups closest to support | $\frac{A_v f_y}{s}$, N/mm | Flexural steel |
|---|---|---|---|---|---|---|---|
| A500 41 MPa | 97.3 | 162.1 | 3.8 | Grade 500 WWF Cold-rolled | MD50 @ 125 mm $f_y$ = 542 MPa | 434 | 4-No. 30 $f_y$ = 467 MPa |
| A400 39 MPa | 98.1 | 163.5 | 3.8 | Grade 400 U-stirrups Hot-rolled | 9.5-mm-dia. @ 120 mm $f_y$ = 407 MPa | 482 | 4-No. 30 $f_y$ = 430 MPa |
| B500 41 MPa | 60.4 | 100.6 | 4.8 | Grade 500 WWF Cold-rolled | MD50 @ 175 mm $f_y$ = 542 MPa | 310 | 4-No. 30 $f_y$ = 467 MPa |
| B400 39 MPa | 61.0 | 101.6 | 4.8 | Grade 400 U-stirrups Hot-rolled | 9.5-mm-dia. @ 170 mm $f_y$ = 407 MPa | 340 | 4-No. 30 $f_y$ = 430 MPa |

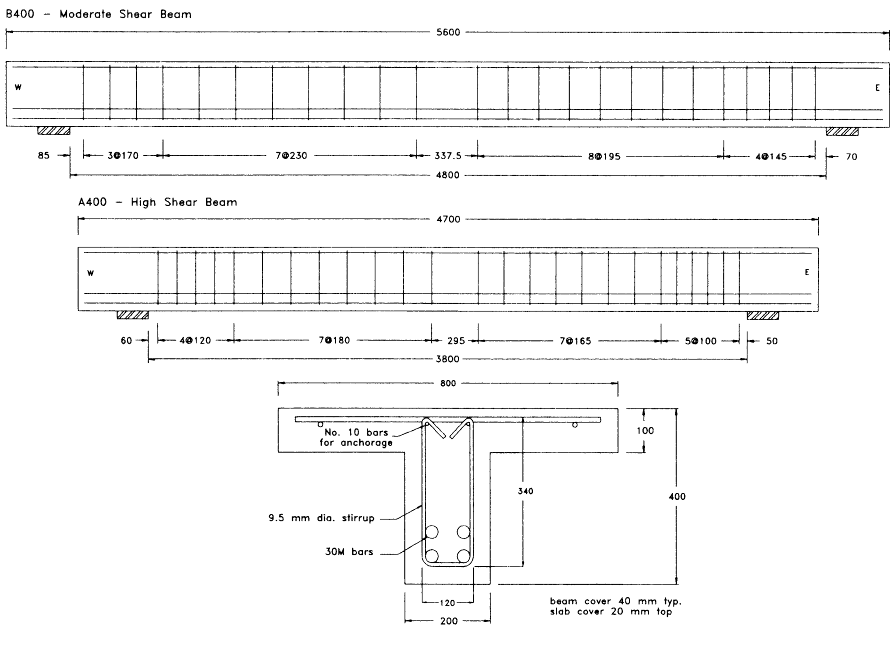


*Fig. 2—Reinforcement details of Beams A400 and B400*

**Table 2 — Properties of reinforcement for beam specimens**

| Size designation | Area, $mm^2$ | $E_s$, MPa | $f_y$, MPa | $f_u$, MPa | $\varepsilon_{rupt}$, percent | Function |
|---|---|---|---|---|---|---|
| Beams A500 and B500 | | | | | | |
| MD50 | 50 | 198,050 | 542 | 595 | 4.2 | Stirrups |
| MD100 | 100 | 200,000 | 596 | 615 | 4.4 | Slab reinforcement |
| No. 30 | 700 | 200,000 | 467 | 712 | — | Longitudinal reinforcement |
| Beams A400 and B400 | | | | | | |
| #3 | 71 | 200,340 | 407 | 655 | 19 | Stirrups |
| No. 10 | 100 | 200,000 | 430 | — | — | Slab reinforcement |
| No. 30 | 700 | 209,400 | 430 | — | — | Longitudinal reinforcement |

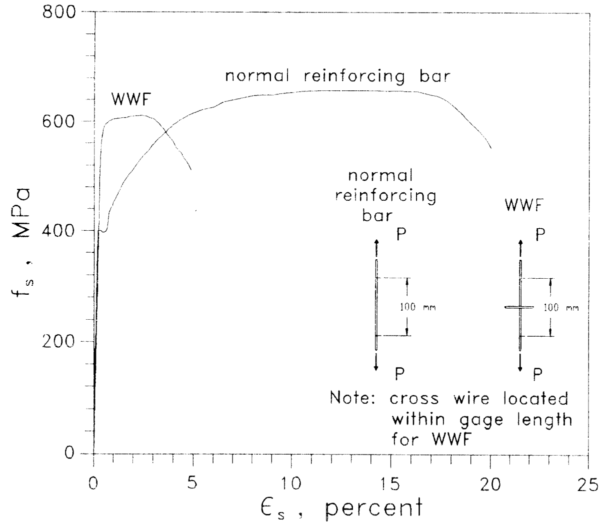


*Fig. 3—Measured stress-strain relationships for cold-rolled, Grade 500 WWF and hot-rolled, Grade 400 stirrups*

Fig. 3 compares the stress-strain relationships of the deformed WWF and hot-rolled deformed reinforcing bars used as stirrup reinforcement in the four beams. For the welded wire fabric, the strains were measured over a gage length of 100 mm (4 in.), which included one cross wire. The 8-mm-diameter (MD50) deformed wire shows a considerably less ductile response, reaching a strain at rupture of 4.2 percent, while the No. 3 (9.5-mm-diameter) reinforcing bars reached a strain of 19 percent at rupture. The average reduction of area after rupture for the 8-mm-diameter deformed WWF was 32 percent.

The 28-day concrete compressive strengths for the beams with WWF stirrups and for those containing U-stirrups were 41.4 and 39.1 MPa, respectively.

## TEST SETUP

A loading apparatus was designed to subject the beams to a simulated uniformly distributed loading, as shown in Fig. 4. Hydraulic rams, which loaded distribution beams under the testing floor, provided equal tensions in the threaded rods. Spreader beams seated on bearing plates on the top surface of the flange provided loads at 250-mm intervals along the length of each specimen, with each hydraulic ram loading 1 linear meter of span. This loading pattern produced a relatively uniform loading on the specimen. Transverse reinforcement, perpendicular to the axis of each beam, was provided in the top of the flange to equilibrate the moment produced by bending of the flanges. The flanges were reinforced with a mat of welded wire fabric with two 11.3-mm-diameter (MD100) deformed wires in the longitudinal direction and two MD100 wires under each bearing plate (see Fig. 1).

Each beam was seated in capping compound on top of 150 x 200-mm bearing plates. Beams A500 and B500 were simply supported on a fixed roller at one end and on a free roller at the other end. Beams A400 and B400, tested by Mailhot, had the same clear span and bearing plates as Beams A500 and B500, but the bearing plates rested directly on the support stands.

## INSTRUMENTATION

All four beams were heavily instrumented to provide detailed strain readings in the webs (see Fig. 5). The mechanical strain targets had a gage length of 100 mm (4 in.). For Beams A400 and B400, the vertical targets were glued directly to the stirrups and strain readings were taken through small access holes in the concrete cover. Beams A500 and B500 had a similar gage layout, but the vertical targets were glued to the concrete surface at the location of the stirrups. In addition to the surface targets, the strains were measured directly on the stirrups at a number of locations. At the location of each stirrup, two vertical strain measurements were taken, in the top and bottom halves of the web (see Fig. 5). At every second stirrup, additional targets were provided to form strain rosettes centered about the top and bottom halves of the web to determine the principal strains and the principal angles of compression. Three sets of targets with a gage length of 200 mm (8 in.) were also glued on the top of the slab centered about midspan to monitor the compressive strains in the concrete. One set of targets was located at midspan at the level of the centroid of the bottom layer of longitudinal reinforcement to measure the tensile strain.

Table 3 — Comparison of measured responses of beams with WWF stirrups and beams with hot-rolled stirrups

| Beam | $M_{cr}$, kNm | $w$ @ $M_{cr}$, kN/m | $V_{cr}$, kN | $w$ @ $V_{cr}$, kN/m | $w$ @ 1st stirrup yield west, kN/m | $w$ @ 1st stirrup yield east, kN/m | $V_{max}$ at support, kN | $w_{max}$, kN/m |
|---|---|---|---|---|---|---|---|---|
| A500 | 37 | 20.0 | 78.4 | 44.9 | 123.0 | 141.2 | 396 | 208.5 |
| A400 | 45 | 25.2 | 82.3 | 47.1 | 128.4 | 167.4 | 398 | 209.4 |
| B500 | 33 | 11.3 | 72.1 | 32.1 | 84.1 | 93.1 | 334 | 139.0 |
| B400 | 40 | 14.0 | 81.3 | 36.2 | 110.6 | 126.4 | 311 | 129.7 |

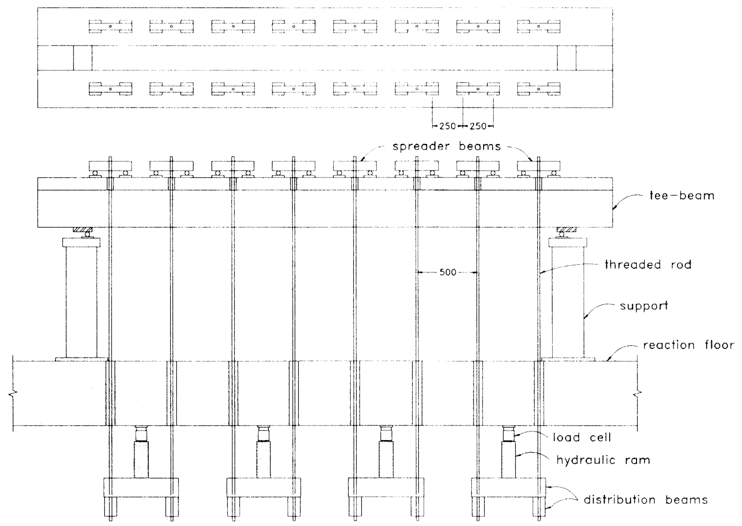


*Fig. 4—Loading apparatus used to simulate uniform load*

A linear voltage differential transducer (LVDT) was used to measure the midspan deflection. Two additional LVDTs were used to monitor any support settlements. Load cells were connected to the system to measure the applied load.

The crack widths were determined at each load stage using a crack width comparator, and labels were placed beside each crack to indicate the crack widths. Photographs at each load step enabled the crack development to be followed.

## EXPERIMENTAL RESULTS

Table 3 and Fig. 6 summarize the important load stages for the four beams. Beams A500 and B500 developed flexural cracks and inclined shear cracks at slightly lower loads than their companion beams, even though their concrete strength $f_c'$ was slightly higher. This may be due to the variability of the tensile strength of concrete and to the small degree of longitudinal restraint caused by the support conditions of Beams A400 and B400. Both Beams A400 and B400 exhibited a slightly stiffer loading response than Beams A500 and B500, indicating a very small restraint effect. As can be seen in Table 3, Beams A500 and A400 reached almost the same ultimate loads, while Beam B500 reached a slightly higher ultimate load than Beam B400.

## STIRRUP STRAINS

The WWF stirrups in Beams A500 and B500 yielded at a lower shear load than the stirrups in Beams A400 and B400 due to the slightly lower yield force provided by the Grade 500 reinforcement (see Table 1 and Fig. 6). In all beams, the stirrups in the west ends reached yield before those in the east ends, due to the larger stirrup spacing in the west ends of the beams. The maximum stirrup strains, measured in the companion specimens, are compared in Fig. 7. These strains are shown at service load levels and at the maximum deflection measured in Mailhot's tests, since Beams A500 and B500

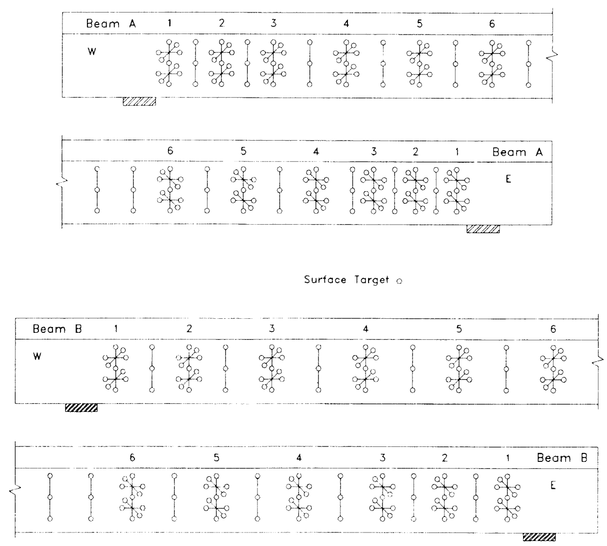


*Fig. 5—Locations of strain targets in web regions*

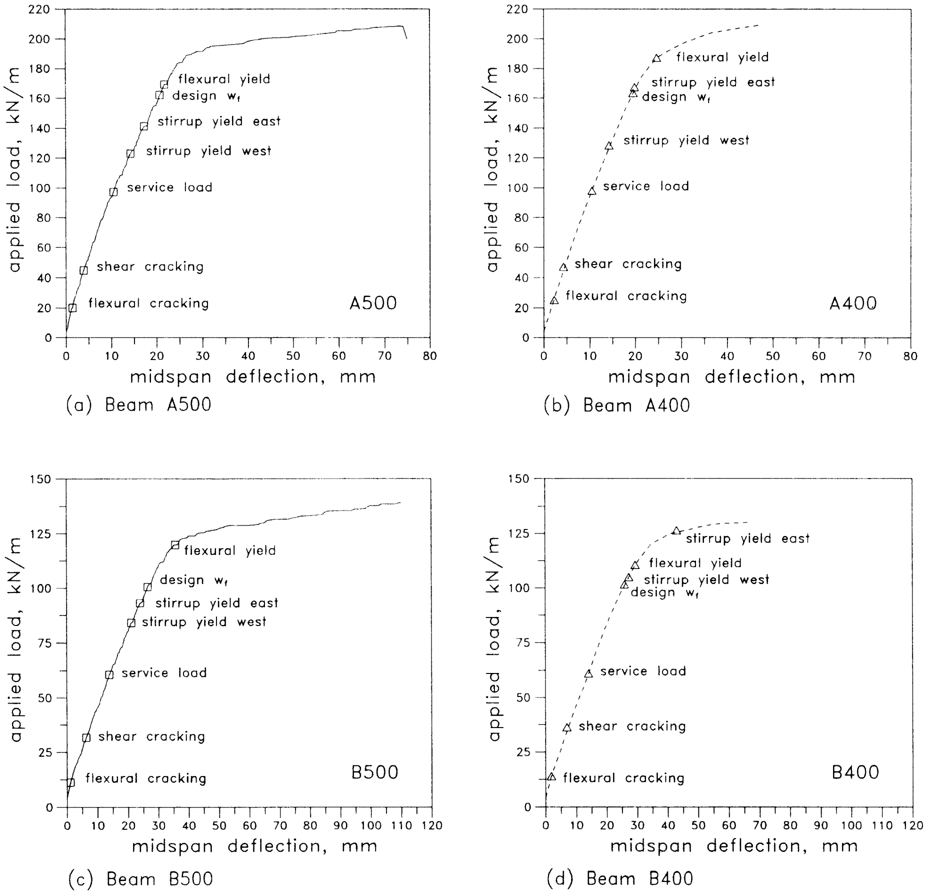


*Fig. 6—Load-deformation responses*

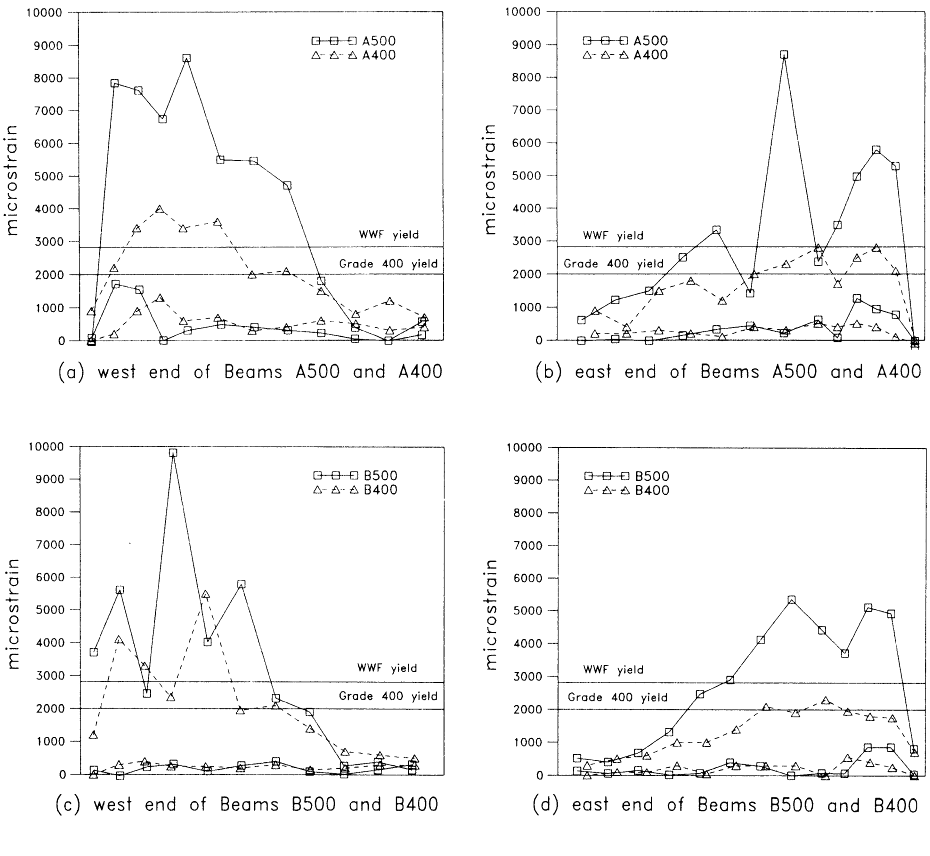


*Fig. 7—Maximum stirrup strains measured at service and ultimate loads*

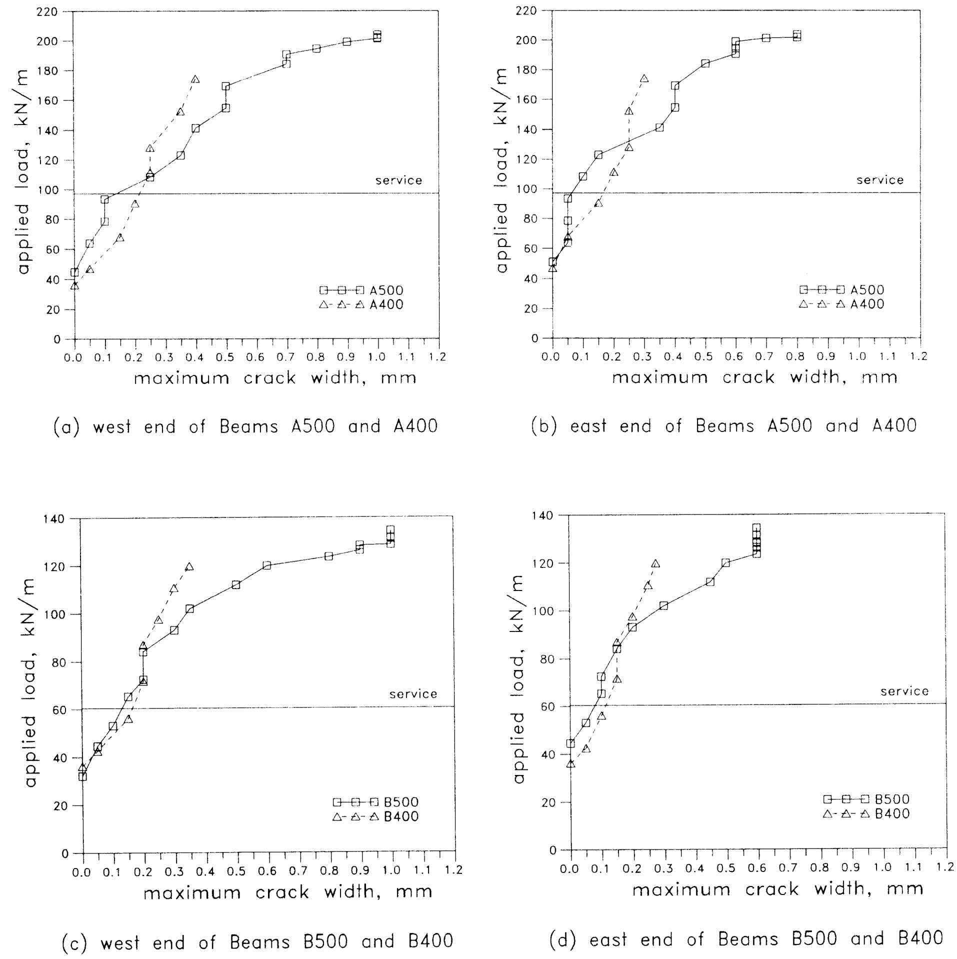


*Fig. 8—Maximum diagonal crack widths*

were both tested to significantly greater deflections (almost 40 percent greater) than Beams A400 and B400. These figures demonstrate that the strains in the stirrups are larger for Grade 500 steel, both at service and ultimate load levels. These larger strains in the welded wire fabric are due to the smaller area of stirrup reinforcement provided in Beams A500 and B500.

## SHEAR CRACK WIDTHS

All four beams had a concrete cover of 40 mm and stirrups with nearly the same yield force per unit length. The use of smaller diameter, higher yield strength welded wire fabric stirrups in Beams A500 and B500 resulted in similar stirrup spacings to those provided in the companion beams, A400 and B400. These features enable a direct comparison of the crack control characteristics of Beams A500 and B500 with their respective companions, Beams A400 and B400.

The load versus maximum shear crack widths for the east and west halves of the beams are shown in Fig. 8. As expected, smaller crack widths were observed in the east ends of the beams due to the larger amounts of shear reinforcement provided. Fig. 8 shows that, at service load levels, smaller shear cracks formed in the beams reinforced with WWF stirrups than in the beams reinforced with hot-rolled stirrups. The smaller crack widths for the beams reinforced with welded wire fabric indicate the improved bond performance of the smaller diameter deformed WWF, which led to a larger number of smaller cracks at service. However, at loads beyond service load level, the beams with welded wire fabric stirrups eventually developed larger cracks than their companion beams. This is due to the smaller area of reinforcement, which must develop larger strains at higher load levels. These tests demonstrate that Grade 500 WWF used as a direct replacement for Grade 400 hot-rolled stirrups provides slightly better crack control at service load levels. In addition, the same shear capacity was attained for these two types of reinforcement. Fig. 9 compares the crack patterns of the four specimens after testing. These crack patterns indicate that the WWF reinforcement was capable of redistributing the stresses between stirrups without displaying a brittle failure mode.

## PREDICTED CAPACITIES

The ACI 318M-89[8] expression for the shear strength of nonprestressed members is

$$\begin{aligned} V_n &= V_c + V_s \\ &= \left(\frac{\sqrt{f_c'}}{6}\right) b_w d + \frac{A_v f_y d}{s} \text{ (MPa and mm)} \\ &= 2\sqrt{f_c'} b_w d + \frac{A_v f_y d}{s} \text{ (psi and in.)} \qquad (1) \end{aligned}$$

**Table 4 — Strength predictions according to ACI 318-89 and modified compression field theory**

| | Test results | | ACI 318M-89 predictions | | | MCFT predictions | | |
|---|---|---|---|---|---|---|---|---|
| Beam | $V_{max}$ at $d$, kN | Failure mode | $V_n$ at $d$, kN | Failure mode | $\frac{V_{max}}{V_{ACI}}$ | $V_n$ at $d$, kN | Failure mode | $\frac{V_{max}}{V_{MCFT}}$ |
| A500 | 332 | Flexure | 200 | Shear | 1.66 | 330 | Flexure | 1.01 |
| A400 | 334 | Flexure | 212 | Shear | 1.58 | 316 | Flexure | 1.06 |
| B500 | 291 | Flexure | 162 | Shear | 1.80 | 267 | Flexure | 1.09 |
| B400 | 272 | Flexure | 169 | Shear | 1.61 | 266 | Flexure | 1.02 |

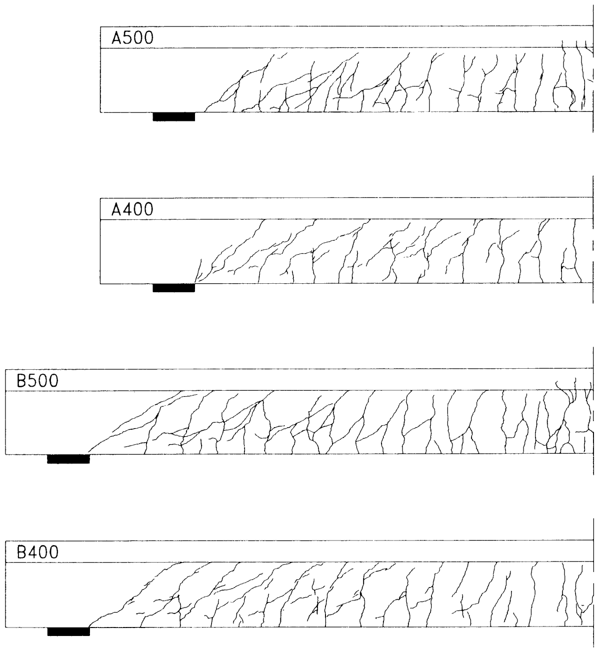


*Fig. 9—Crack patterns of west ends of beams after testing*

where

$V_c$ = nominal shear strength
$V_s$ = nominal shear strength provided by shear reinforcement
$f'_c$ = specified compressive strength of concrete
$b_w$ = web width
$d$ = distance from extreme compression fiber to centroid of longitudinal reinforcement
$A_v$ = area of shear reinforcement within distance $s$
$f_y$ = specified yield strength of nonprestressed reinforcement
$s$ = spacing of shear reinforcement

This expression uses a constant value of the shear stress carried by the concrete of $0.167\sqrt{f'_c}$ MPa ($2\sqrt{f'_c}$, psi) and assumes a 45-deg truss.

The predicted capacities of the four beams, computed using the expressions of ACI 318M-89 and the measured material properties, are shown in Table 4. Since the stirrups were more closely spaced in the east end of the beams, the west ends governed their design capacities. Although the ACI Building Code limits the yield stress of shear reinforcement to 400 MPa, the yield stress measured at a strain of 0.35 percent was used in determining the shear capacities in Table 4. Even with the higher yield stress, the predictions using the ACI expressions are very conservative.

The modified compression field theory[13,14] accounts for strain compatibility and uses both tensile and compressive stress-strain relationships for the diagonally cracked concrete. The shear strength is given as

$$\begin{aligned} V_n &= V_c + V_s \\ &= \beta\sqrt{f'_c}\,b_w d_v + \frac{A_v f_y}{s}\frac{d_v}{\tan\theta} \end{aligned} \tag{2}$$

where

$\beta$ = residual tensile stress factor
$\theta$ = principal angle of compression, deg

The value of the residual tensile stress factor is given by the following expressions

$$\begin{aligned} \beta &= \frac{\alpha_1\alpha_2 0.33\cot\theta}{1+\sqrt{500\varepsilon_1}}\text{(MPa)} \\ &= \frac{\alpha_1\alpha_2 4\cot\theta}{1+\sqrt{500\varepsilon_1}}\text{(psi)} \end{aligned} \tag{3}$$

where

$\alpha_1$ = factor accounting for bond characteristics of reinforcement (1.0 for deformed bars)
$\alpha_2$ = factor accounting for type of loading (1.0 for short-term monotonic loading)
$\varepsilon_1$ = principal tensile strain

but

$$\begin{aligned} \beta &\le \frac{0.18}{0.3+\frac{24w_{cr}}{a+16}}\text{(MPa and mm)} \\ &\le \frac{2.16}{0.3+\frac{24w_{cr}}{a+0.63}}\text{(psi and in.)} \end{aligned} \tag{4}$$

where

$w_{cr}$ = crack width
$a$ = maximum aggregate size

This equation is used for nonprestressed and prestressed

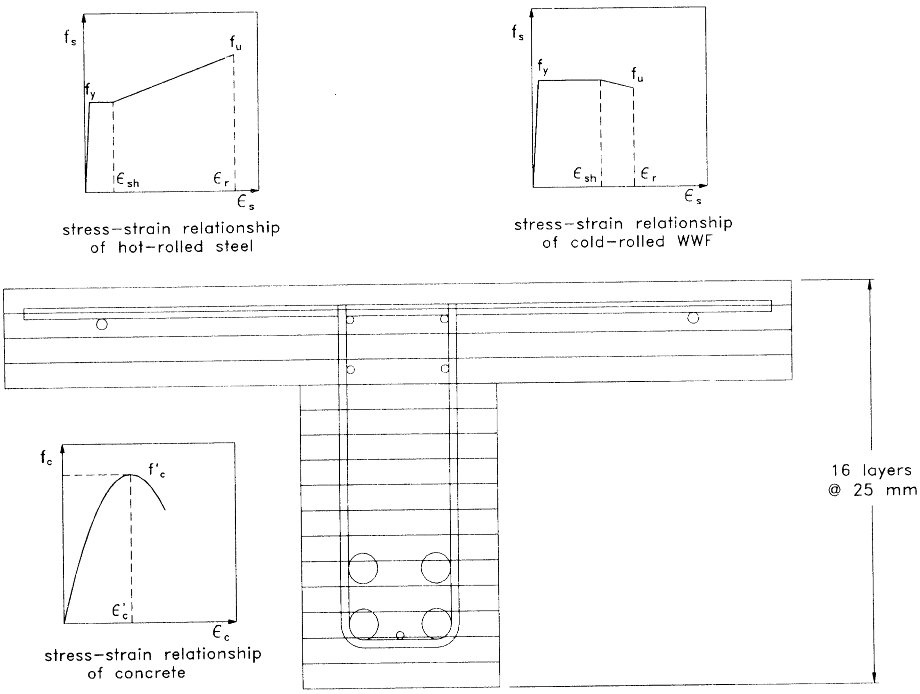


*Fig. 10—Discretization of beam cross section and material stress-strain relationships used in RESPONSE predictions*

members as well as members with axial tension and axial compression. The tensile stress factor $\beta$ and the angle of principal compression $\theta$ depend on the level of shear stress and longitudinal strain in the web. Hence, unlike the ACI expression $\beta$ and $\theta$ are not constant values.

The computer program RESPONSE,[14,15] based on the modified compression field theory, was used to predict the ultimate capacities of the four beams. This computer program combines a plane section analysis for flexure with the modified compression field analysis for shear. Fig. 10 illustrates the manner in which the cross section is discretized into horizontal layers and also shows the material stress-strain characteristics used in the analysis. The shear capacities from these analyses are given in Table 4 for the critical section located at a distance *d* from the support face of the west ends of the beams. These predictions accounted for the shear-moment interaction at these sections. From analyses at different sections along each beam, the beams were predicted to fail in flexure just before failing in shear (see Table 4).

## CONCLUSIONS

The tests on the full-scale beams resulted in the following conclusions:

1. The inclined shear cracks were smaller at service load levels for the beams reinforced with smaller diameter Grade 500 deformed welded wire fabric cages than those of the companion beams, reinforced with equivalent amounts (i.e., the same $A_v f_y / s$) of hot-rolled, Grade 400 stirrups.

2. The two deformed cross wires, welded at the top of the stirrup cage, detailed in accordance with the ACI Building Code, provided sufficient anchorage to develop significant strains in the stirrups.

3. The cold-rolled deformed welded wire fabric stirrups exhibited large strains and sufficient ductility to redistribute the stresses in the stirrups to avoid a sudden, brittle shear failure.

4. For the four beams tested, the predictions of shear capacity using the modified compression field theory are more accurate than the predictions using ACI 318M-89 expressions.

5. The maximum yield stress to be used in shear design calculations as specified in the ACI Building Code is $f_y = 400$ MPa. This limit results in overly conservative estimates of the shear strength of the beams reinforced with Grade 500 welded wire fabric. Since the welded wire fabric is able to develop significant strains and exhibits sufficient ductility to redistribute the strains to avoid brittle shear failures, its nominal yield stress of $f_y = 500$ MPa could be used in design calculations.


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## CONVERSION FACTORS

1 in. = 25.4 mm
1 ksi = 6.895 MPa
1 kip = 4.448 kN

## NOTATION

$a$ = maximum aggregate size
$A_s$ = cross-sectional area of steel reinforcement

$A_v$ = cross-sectional area of stirrup reinforcement within distance s
$b_w$ = effective web width
$d$ = distance from extreme compression fiber to centroid of longitudinal reinforcement
$d_v$ = effective shear depth, taken as perpendicular distance between resultants of tensile and compressive forces due to flexure, but not less than $0.9d$
$E_s$ = modulus of elasticity of reinforcing steel
$f'_c$ = compressive strength of concrete
$f_u$ = tensile strength of reinforcement
$f_y$ = yield stress of reinforcing steel
$\ell_n$ = clear span
$M_{cr}$ = cracking moment resistance of concrete
$s$ = spacing of stirrups
$V_{ACI}$ = nominal shear capacity from ACI 318M-89 expressions
$V_c$ = shear resistance provided by concrete
$V_{cr}$ = cracking shear resistance of concrete
$V_f$ = factored shear force
$V_{max}$ = maximum applied shear
$V_{MCFT}$ = nominal shear capacity from modified compression field theory
$V_n$ = nominal shear strength
$V_s$ = shear capacity of stirrups
$V_{se}$ = shear at service load level
$w$ = uniform loading on beam
$w_{cr}$ = crack width
$w_f$ = factored design loading per unit length
$w_{max}$ = maximum applied uniform load
$w_{se}$ = service loading per unit length
$\beta$ = residual tensile stress factor
$\varepsilon_{rupt}$ = strain in reinforcing bar at rupture
$\varepsilon_1$ = principal tensile strain, tension positive
$\theta$ = angle of inclination of diagonal compressive stresses measured from longitudinal axis of member, deg

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